

# An Unmanned Ground Vehicle-aided Task Exchange System Of Small Air Vehicles For Remote Surveillance Missions

Serkan ÇAŞKA<sup>1</sup>, Ahmet GAYRETLİ<sup>2</sup>

<sup>1</sup> Mechatronic Engineering Department, Afyon Kocatepe University, serkancaska@aku.edu.tr

<sup>2</sup> Mechatronic Engineering Department, Afyon Kocatepe University, agayretli@aku.edu.tr

**Abstract**— Small/portable unmanned air vehicles which supply their energy from electric batteries have been successfully used in applications of intelligence, surveillance and reconnaissance-based missions gradually. Despite their increasing usage, studies which focus on S-UAVs limited battery capacities has not been completely dealt in the literature. This obstructs the usage of small unmanned air vehicles in long range and unremitting mission scenarios. In addition, small unmanned air vehicles have been supported with unmanned ground vehicles to carry out surveillance-based missions efficiently in recent researches. However, studies including collaborative teams with unmanned air and ground vehicle are limited in literature. In this paper, a surveillance system that is based on collaboration of two small unmanned air vehicles and a transporter unmanned ground vehicle was proposed. In order to provide the continuity of surveillance mission, an assigning and directing algorithm that considers battery charge level of the small unmanned air vehicles was developed within the proposed system. Developed algorithm assigns tasks to unmanned air vehicles and changes their role in surveillance mission by checking their battery levels. The proposed system was examined with tests in simulation and outdoor environment in a specified range and unmanned air vehicles completed surveillance mission by making a successful task exchange during their mission.

**Keywords**— Unmanned Ground vehicle, Unmanned Air vehicle, Multi Robot Collaboration, Missions Of Intelligence Surveillance And Reconnaissance, Battery Limitations Of Small Unmanned Air Vehicle, Proportional Navigation, PID Controller

## INTRODUCTION

Small unmanned air vehicles (S-UAV) have become one of the most preferred air platform for intelligence, surveillance and reconnaissance (ISR)-based missions in recent years. A small UAV is an unmanned air platform that is enough to be transportable. S-UAV-based unmanned systems have been used for information gathering in various applications that are carried out in border security, environment mapping and so on [1], [2]. ISR can be defined as information gathering from something or somewhere for human operators [3]. By using multiple S-UAVs, the time that is spent to carry out ISR-based missions can be minimized [4]. S-UAVs have been successfully used in applications of ISR-based missions gradually. [5] proposed a prototype of an autonomous helicopter that offers a cheap platform for ISR based missions. [6] presented a study of multiple S-UAVs performed for an ISR-based task that aims to guarantee to visit all the parts of a the target area continuously. In addition to increasing S-UAV usage, recently, there have been various research that were carried out by combining S-UAVs and unmanned ground vehicles (UGV) to perform ISR-based missions. [7] presented an advanced framework of crowd control that is carried out with S-UAVs and UGVs. [8] proposed a communication and control method for ISR-based missions including UGVs and S-UAVs. [9] proposed a system that is carried out with the collaboration of UGV and S-UAV. Proposed system performs the mission of periodical surveillance in an indoor test area. [10] presented two cooperation methods between a S-UAV and UGV. Developed two methods proposed practical advices to coordinate S-UAVs and UGVs on an outdoor test environment where a chemical substance spread is simulated within an exercise of train accident scenario. [11] introduced a visual based method that will be used in coordination of a S-UAV and an UGV to perform an ISR-based mission. S-UAV tracks and also carry out auto-landing on a moving UGV. [12] presented an experimental collaborative study including a S-UAV and UGVs. The experiment demonstrated that detection of pedestrians and vehicles is possible by using an autonomous unmanned vehicle based system under real dynamic environment conditions. [13] presented an ISR-based system of UGVs and S-UAVs that is developed to detect the location of the victims of a possible earthquake. [14] introduced a method for multi-target tracking by using S-UAVs. The proposed method tries to eliminate tracking interruptions because of obstacles and other S-UAVs in test area. Figure 1 shows data that was obtained from web of science database and demonstrates number of the studies including UAVs (TS1), UGVs (TS2) and cooperation between UAVs and UGVs (TS3). It is clear that the number of studies including only UAVs and UGVs have showed a big increase in recent years. However number of studies including cooperation of UAVs and UGVs has remained limited [15].

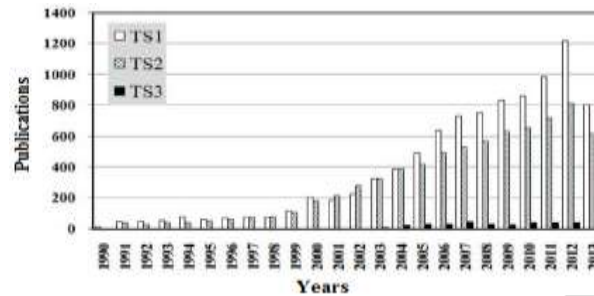


Figure 1: Web of Science data that shows the number of publications including unmanned vehicles in recent years [15]

In literature, despite various studies focused on ISR-based missions with teams including S-UAVs and UGVs, few of them consider battery limitations of S-UAVs and persistence of the mission. Furthermore, carrying the S-UAVs to mission areas by using unmanned ground vehicles is still a new study field for researchers. Unlike the many of the studies in related literature, the proposed system takes into account the energy limitations of batteries replaced on S-UAVs. Required energy for S-UAVs is generally provided from batteries that has Li-Po (lithium polymer) structure. S-UAVs can fly and communicate several minutes via consuming their Li-Po batteries. When an S-UAV consumes its battery charge in an ISR-based mission, in order to continue its fly, a new battery with complete charge must be provided. However, recharge or swapping operation of a S-UAV batteries need several minutes. Therefore, an auxiliary S-UAV must be ready to assist the other one in target mission area. For this reason, the presented system in this paper was developed to carry out ISR-based missions by using two S-UAVs that were assigned to help each other.

By using our proposed system, an efficient surveillance can be performed in mission areas with insecure conditions for a human. Besides, our proposed system will give a new perspective to ISR-based unmanned system developers to design more effective systems for the scenarios that require long time. The developed system can be implemented in mission areas as a quick and a low budget surveillance method. Our proposed system is suitable to implement in surveillance of power production centers, surroundings of military zones, and so on. S-UAV cooperation method of our proposed system can be used not only with unmanned ground systems but also with manned ground vehicles. However, in order to demonstrate the collaboration capacity of the proposed system, S-UAVs were used in cooperation with an unmanned ground vehicle. In this work, the authors focused on the cooperation of unmanned air and ground vehicles while air vehicles are carrying out a continuous ISR-based mission. However, in literature, various studies were executed on automatic swap and recharge systems for batteries of S-UAVs [16], [17]. It shows that a battery recharge or a battery swapping system can be used to provide the continuity of our proposed system. Design and implementation of a battery swapping mechanism to our proposed system was decided to realize in future project.

S-UAVs that can take off and land vertically do not need a runway and this makes them one of the most preferred air platforms for ISR-based missions. In our study, unmanned air platforms were designed as quad-copters and unmanned ground platform was designed as a differential drive robot. Ground robot was developed as a transporter vehicle for two quad-copters where a take-off and landing platform was placed on it.

## THE PROPOSED SYSTEM

The proposed system consists of two quad-copter S-UAVs, a transporter UGV, a central computer, S-UAV assigning/directing algorithm that run in central computer, a human operator who watches data of unmanned vehicles and also sends his commands to the vehicles. General structure of the proposed system is as shown in Figure 2.



Figure 2: General structure of the proposed system

The proposed system was composed in both simulation and real environment and also was implemented within a sample application. This application is implemented through exchanging the tasks of two S-UAVs. An UAD (UAV assigning and directing) algorithm developed and run on Matlab software guides S-UAVs during their mission. In sample application, one of the S-UAV (assigned S-UAV) was directed manually by a human operator. When battery charge of the assigned S-UAV exceeded a pre-defined level, the auxiliary S-UAV was sent to take on the task from the assigned S-UAV. Sample application demonstrated that the proposed system is proper for the applications which the S-UAVs are directed manually. Since controlling a S-UAV can include unpredictable and dynamic movements of S-UAVs, our proposed system can be used within the dynamic applications such as target tracking, formation flight and so forth.

According to the sample application of the proposed system, after stopping the transporter UGV on a proper mission point in a mission area, one of the S-UAV takes off and is directed with manual commands of a human operator. If battery level of the assigned S-UAV exceeds a pre-defined TEDL (task exchange demand level) during its movement, the UAD algorithm directs the auxiliary S-UAV to a location that was specified by considering current position of the assigned S-UAV. In order to not to cause a collision of S-UAVs, the UAD algorithm indicates the target position of auxiliary S-UAV as the position that is three meters far to current position of the assigned S-UAV in z axis. Furthermore, two meters error margin was specified for the target position of the auxiliary S-UAV. Therefore, the UAD algorithm assumes that the auxiliary S-UAV reached its target point when it becomes closer than two meters to the target point. The assigned S-UAV is sent onto the transporter UGV when the auxiliary S-UAV arrives the target coordinates. In addition, the assigned S-UAV's battery level exceeds a specified ERL (emergency return level) before the auxiliary S-UAV arrives the target position, the assigned S-UAV urgently returns to the transporter UGV without regarding the current position of the auxiliary S-UAV.

The position of the assigned S-UAV (tracked or target S-UAV) is defined as  $U_T \in \mathbb{R}^3$ . The auxiliary S-UAV's position is defined as  $U \in \mathbb{R}^3$ . The position error between the auxiliary S-UAV with respect to and the target position can be defined as in Equation (1).

$$Ue = \sqrt{(U_Tx - Ux)^2 + (U_Ty - Uy)^2} \quad (1)$$

If PID method is used in tracking of the assigned S-UAV, it will try to decrease the error between the auxiliary S-UAV's position and the target. However, in this study, our aim is to make the auxiliary S-UAV catch the assigned S-UAV as quickly as possible. Tracking a moving target with PID method is not the best approach for our purpose. Thus, a PN (proportional navigation) strategy that was inspired from Realistic True Proportional Navigation (RTPN) method was developed. RTPN method is proper for the quad-copter's lateral navigation and our RTPN-based method was developed for the guidance of the auxiliary S-UAV [18]. In developed PN strategy, the additional distances for meeting (adm) were specified for x and y directions to guarantee the intersection of S-UAVs. In Equation (2) and Equation (3), adm values were defined respectively in x and y directions.

$$x^{adm} = (U_Tx - U_Tx)\lambda \quad (2)$$

$$y^{adm} = (U_Ty - U_Ty)\lambda \quad (3)$$

In Equation (2) and Equation (3), adm values of x and y directions are calculated by multiplying  $\lambda$  that is the navigation coefficient and the absolute value of the position difference between the auxiliary S-UAV and the assigned S-UAV.

In order to guarantee the intersection of S-UAVs, estimated meeting positions were defined. In Equation (4) and Equation (5), estimated meeting positions of S-UAVs were calculated by adding adm values to current position of the assigned S-UAV.

$$U_T^{emp}x = U_Tx + x^{adm} \quad (4)$$

$$U_T^{emp}y = U_Ty + y^{adm} \quad (5)$$

Parameters of adm and emp that were calculated within PN method are shown in Figure 3.



Figure 3: PN method for tracking of the assigned S-UAV

The auxiliary S-UAV tries to reduce the difference between its altitude and altitude of the assigned S-UAV and also tries to equalize its yaw angle to yaw angle of the assigned S-UAV. In proposed system, tracking of the auxiliary S-UAV's altitude and yaw angle were performed by using traditional PID method.

In sample application, a parameter of  $mr$  (mission range) that represents the furthest reachable distance for S-UAVs was defined. The value of  $mr$  should be defined by the human operator by taking account S-UAV battery capacities. The worst situation for the assigned S-UAV is to exceed a specified IRL when it is on the furthest point from the transporter UGV. Therefore, in order to guarantee return of S-UAVs to transporter UGV safely,  $mr$  should be regarded in calculation of ERL. The auxiliary S-UAV tries to equalize its yaw angle to yaw angle of the assigned S-UAV while it is reaching sepat (start/end point for attitude tracking). The auxiliary S-UAV turns into the new assigned S-UAV when it arrives the target point and the old assigned S-UAV turns into the transporter UGV by visiting sepat. During the tracking process, the assigned S-UAV might exhibit quick and varying movement, therefore the time will pass for meeting of S-UAVs can not be predicted exactly. Thus, TEDL also can not be defined exactly and was regarded as twice ERL. During the assigned S-UAV tracking process of the auxiliary S-UAV, if the charge level of the returning assigned S-UAV's battery exceeds ERL, the UAD algorithm urgently directs the assigned S-UAV onto the transporter UGV. In this situation, when charge level of the assigned S-UAV exceeds ERL, the UAD algorithm registers the latest recorded coordinates of the returning assigned S-UAV and takes into account it as the target position for the auxiliary S-UAV. When the charge level of the assigned S-UAV's battery exceeds TEDL, at first the UAD algorithm directs the auxiliary S-UAV to the sepat and then directs it to the current position of the assigned S-UAV. Similarly, the assigned S-UAV visits sepat before it is directed to land on the transporter UGV. If the altitude of sepat is high to neglect, it must be taken into account in calculation of TEDL. TEDL and ERL are expressed as in Equation (6) and Equation (7) respectively.

$$TEDL = (mr + \text{altitude of sepat}) * 2 * cf \quad (6)$$

$$ERL = (mr + \text{altitude of sepat}) * cf \quad (7)$$

In sample application, after the assigned S-UAV lands on the transporter UGV, it becomes the new auxiliary S-UAV.

In literature, studies that were executed on consumption of electrical batteries include approximate models and there is not a common consumption formulation for batteries of S-UAVs [19]. Therefore, power consumption of S-UAVs was generated with experiments that were carried out in real flight tests. Power consumption experiments of S-UAVs were executed in windless environment. After power consumption experiments, it was detected that a quad-copter S-UAV consumes 0.093% of its battery charge, while it is passing each meter during its vertical and horizontal movements. This detected consumption value was considered as consumption factor ( $cf$ ) in this study. This means that a quad-copter S-UAV used in our system can move 1080 meters approximately in each direction with a completely charged battery (2200 mAh battery with lithium polymer structure). The consumption factor might be changed by human operator depending on the loads of S-UAVs and the weather conditions. In our study, a simple approach was used in define power consumption and TEDL and ERL of S-UAVs. However, detailed consumption approaches with various parameters might be used within the proposed system.

## DYNAMIC MODELS OF UNMANNED VEHICLES

Dynamic models of quad-copter S-UAVs and UGV were obtained to simulate the proposed system. Then the vehicle models were formed in Matlab-Simulink. Finally, sample application that was carried out with the proposed system was visualized by using 3D VRML builder software that can connect to Simulink models of the quad-copter S-UAVs and UGV.

In this study, quad-copter was used as S-UAV. As illustrated in Figure 4, quad-copter is an air vehicle with four rotors. By changing angular velocities of rotors, movements of throttle, roll, pitch and yaw are obtained [20].

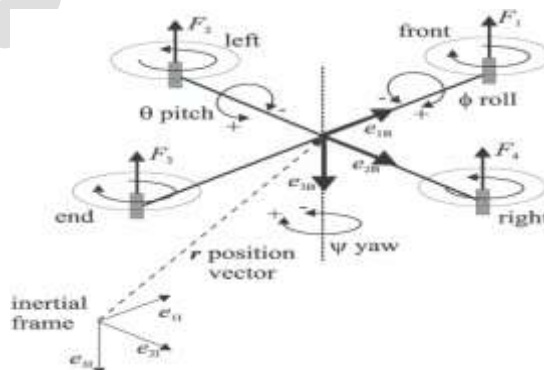


Figure 4: Configuration and structure of a quad-copter [20]

In order to derive the quad-copter's dynamic model, the inertial frame must be considered as showed in Figure 4. The vector of  $\Omega^T = (\phi, \theta, \psi)$  that represents the quad-copter's orientation is obtained by using Euler angles which are  $\phi$  (roll angle),  $\theta$  (pitch angle) and  $\psi$  (yaw angle).  $r^T = (x, y, z)$  is the vector that represents the position of quad-copter in the inertial frame.  $R$  that was given in Equation (8) is the rotation matrix that provides the transformation of the vectors from the body frame of the quad-copter to inertial frame. In representation of  $R$ , for instance,  $c\phi$  indicates  $\cos\phi$  and  $s\theta$  indicates  $\sin\theta$  [21].

$$R = \begin{pmatrix} c\psi c\theta & c\psi s\theta s\phi - s\psi c\phi & c\psi s\theta c\phi + s\psi s\phi \\ s\psi c\theta & s\psi s\theta s\phi + c\psi c\phi & s\psi s\theta c\phi - c\psi s\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{pmatrix} \quad (8)$$

If we define the forces of the propellers, the thrust force is equal to  $F_i = b \cdot \omega_i^2$  and it is obtained from  $i^{th}$  ( $i=1,2,3,4$ ) rotor. In this representation,  $b$  is the thrust factor and  $\omega_i$  is  $i^{th}$  rotor's the rotational speed. The total thrust force generated by the four rotors is written as in Equation (9).

$$T = \sum_{i=1}^4 |F_i| = b \sum_{i=1}^4 \omega_i^2 \quad (9)$$

By using  $T$ , differential equations that represent the quad-copter's acceleration are written as in Equation (10).

$$\begin{pmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{pmatrix} = g \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} - R \frac{T}{m} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \quad (10)$$

Another differential equation are written as in Equation (11) by using the matrix  $I$  which is diagonal matrix including the inertias of  $x$ ,  $y$ ,  $z$  axis and  $M$  that represents the torque implemented to the quad-copter's body and  $M_G$  that represents the gyroscopic torques.

$$I\dot{\Omega} = -(\dot{\Omega} \times I\dot{\Omega}) - M_G - M \quad (11)$$

$M$  can be represented as in Equation (12).

$$M = \begin{pmatrix} Lb(\omega_1^2 - \omega_3^2) \\ Lb(\omega_2^2 - \omega_4^2) \\ d(\omega_1^2 + \omega_3^2 - \omega_2^2 - \omega_4^2) \end{pmatrix} \quad (12)$$

In representation of the  $M$ ,  $d$  defines the drag factor and  $L$  represents distance between the propellers and center of the quad-copter. The gyroscopic torques that are generated by rotations of the vehicle are written as in Equation (13).

$$M_G = I_R \left( \dot{\Omega} \times \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \right) (\omega_1 - \omega_2 + \omega_3 - \omega_4) \quad (13)$$

The real input variables of the quad-copter are  $\omega_i$  of each rotor. However, transforming the real inputs to artificial inputs is more convenient. Artificial inputs are defined as in Equation (14) to Equation (17).

$$u_1 = (\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2) \quad (14)$$

$$u_2 = (\omega_1^2 - \omega_3^2) \quad (15)$$

$$u_3 = (\omega_2^2 - \omega_4^2) \quad (16)$$

$$u_4 = (\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2) \quad (17)$$

In Equation (14) to Equation (17),  $u_1$  is the total thrust force;  $u_2$  is the force that generates roll torque;  $u_3$  is the force that generates pitch torque and  $u_4$  is the force that generates yaw torque. In addition, gyroscopic torques that were given in Equation (18) depend on the rotational speeds of the rotors and also depend on the vector of the artificial inputs that is defined as  $u^T = (u_1, u_2, u_3, u_4)$ .

$$g(u) = \omega_1 - \omega_2 + \omega_3 - \omega_4 \quad (18)$$



Complete model of a quad-copter is obtained in Equation (19) to Equation (24) through evaluating Equation (10) and Equation (11):

$$\ddot{x} = -(\cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi)\frac{u1}{m} \quad (19)$$

$$\ddot{y} = -(\cos\psi\sin\theta\sin\phi - \cos\psi\sin\phi)\frac{u1}{m} \quad (20)$$

$$\ddot{z} = g - \cos\theta\cos\phi\frac{u1}{m} \quad (21)$$

$$\ddot{\phi} = \dot{\theta}\dot{\psi}\left(\frac{I_y - I_z}{I_x}\right) - \frac{I_R}{I_x}\dot{\theta}g(u) + \frac{L}{I_x}u2 \quad (22)$$

$$\ddot{\theta} = \dot{\phi}\dot{\psi}\left(\frac{I_z - I_x}{I_y}\right) + \frac{I_R}{I_y}\dot{\phi}g(u) + \frac{L}{I_y}u3 \quad (23)$$

$$\ddot{\psi} = \dot{\theta}\dot{\phi}\left(\frac{I_x - I_y}{I_z}\right) + \frac{1}{I_z}u4 \quad (24)$$

Six controllers were used to completely control a quad-copter S-UAVs. The inner controllers of the quad-copter are Z, Phi, Theta and Psi controllers. The outer controllers are X and Y controllers. By generating pitch and roll angles for inner controllers, outer controllers provide the quad-copter's navigation to desired positions. Controllers of the quad-copter UAVs are shown in Figure 5.

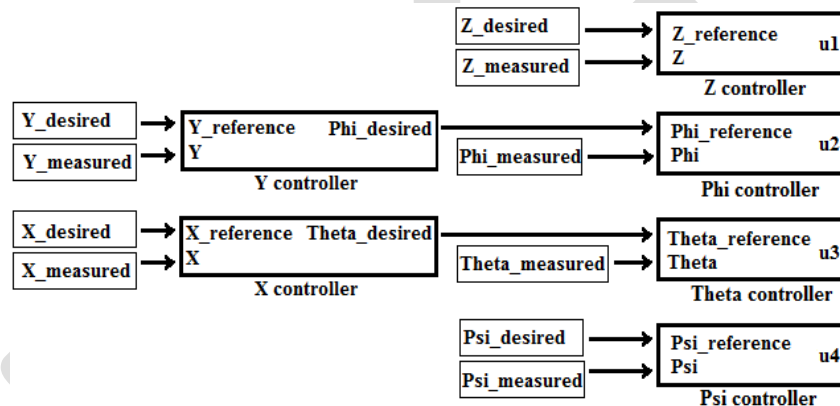


Figure 5: Controllers of the quad-copter

The controllers of the quad-copters were designed by using conventional PID (proportional integral derivative) method [22]. Parameters of controllers were defined with Hand-Tuning procedure that is based on tuning P, I and D parameters respectively and is a convenient method for tuning PID parameters of quad-copters.

In proposed system, transporter vehicle was a differential drive UGV that has two independent wheels which were controlled by using electrical motors. As can be seen in Figure 6,  $a$  represents the distance between two wheels, and  $r$  represents the radius of each wheel.

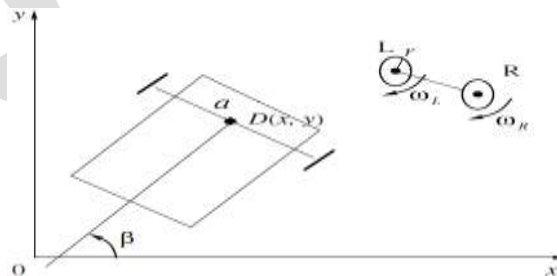


Figure 6: Configuration of differential drive vehicle [23]

In mathematical presentation of movement of a differential drive UGV, firstly Equation 25 to Equation 27 should be written.

$$\dot{x} = V\cos\beta \quad (25)$$

$$\dot{y} = V\sin\beta \quad (26)$$

$$\dot{\beta} = \omega \quad (27)$$

In Equation 25 and Equation 26,  $V$  represents UGV's linear velocity,  $\omega$  represents UGV's angular velocity and  $\beta$  represents the UGV's orientation. Angular and linear velocities of UGV are derived with angular velocities of left ( $\omega_L$ ) and right ( $\omega_R$ ) wheels in Equation 28 and Equation 29.

$$\omega = \frac{r}{a} (\omega_R - \omega_L) \quad (28)$$

$$V = \frac{r}{2} (\omega_R + \omega_L) \quad (29)$$

Equation 30, Equation 31 and Equation 32 are derived, if we apply Equation 28 and Equation 29 into Equation 25 to Equation 27.

$$\dot{x} = \frac{r}{2} (\omega_R + \omega_L) \cos \beta \quad (30)$$

$$\dot{y} = \frac{r}{2} (\omega_R + \omega_L) \sin \beta \quad (31)$$

$$\dot{\beta} = \frac{r}{a} (\omega_R - \omega_L) \quad (32)$$

In our sample application, the role of the transporter UGV was limited to transport the quad-copter S-UAVs to target mission area. The obtained mathematical model that was derived by considering kinematic constraints was used to represent the movement of the transporter UGV. In sample application, a human operator directed the transporter UGV with manually. Commands of human operator were converted to desired angular velocities for the wheels of transporter UGV.

## SIMULATION TEST FRAME OF THE DEVELOPED SYSTEM

Simulation of the proposed system was achieved within Matlab/Simulink software by using mathematical models of the unmanned vehicles. Our sample application was visualized via VRML builder software.

In simulation of our developed system, an operator directs one of the S-UAVs with manual commands. Directing of S-UAV is performed by considering mr. The auxiliary S-UAV is directed to take on the task of the assigned S-UAV when battery charge level of the assigned S-UAV exceeds TEDL. Figure 7 indicates the connections among Simulink models of unmanned vehicles, UAD algorithm, VRML builder and Graphical user interface.

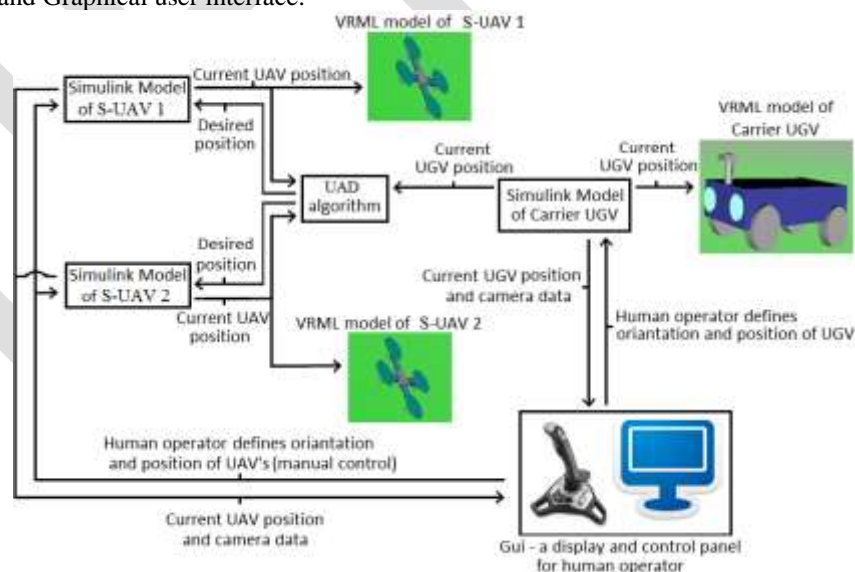


Figure 7: Simulation configuration of the proposed system

Since the proposed system is developed as a visual ISR-based mission, virtual camera objects were integrated to the S-UAVs and the transporter UGV. Figure 8 indicates unmanned vehicles created in VRML builder software.

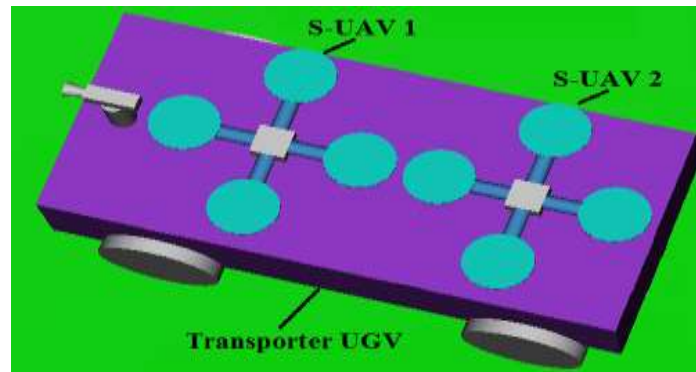


Figure 8: Virtual unmanned vehicles created in VRML builder

## EXPERIMENTAL TEST FRAME OF THE DEVELOPED SYSTEM

In experimental tests of our developed system, ArduCopter autopilot boards were used to control the S-UAVs and ArduRover boards was used to control the transporter UGV.

In order to display data of the unmanned vehicles and to send the commands of UAD algorithm and human operator, Mission Planner that is an open source ground station software developed for unmanned air and ground vehicles was used.

Experimental tests of our developed system were achieved via a computer where the Mission Planner and Matlab programs run, APM control boards and sensors that were placed on unmanned vehicles and wireless communication devices.

Central computer was used as a ground station that operates Mission Planner and Matlab software and provides the connection between these programs. Human operator watches onboard cameras and access sensor data of the unmanned vehicles and send his commands to vehicles by using a graphical user interface in central computer. In experimental tests, human operator directs one of the quad-copter S-UAVs with manual commands. S-UAVs are directed within mr. While the assigned S-UAV is directed by the human operator, the assigned S-UAV sends the charge level of its battery to Mission Planner that it is in connection. Mission Planner writes the current position of the assigned S-UAV into a txt file. Mission Planner of the assigned S-UAV writes its battery charge level into another txt file. The UAD algorithm that is running on Matlab reads the charge level of the assigned S-UAV's battery and sends the take-off command to the auxiliary S-UAV that is on the transporter UGV when the charge level of the assigned S-UAV' battery exceeds TEDL. Then, the auxiliary S-UAV is assigned by the UAD algorithm to take on the task of the assigned S-UAV when the auxiliary S-UAV reaches sepat. By regarding the task take on command, the auxiliary S-UAV starts to track the assigned S-UAV. When the S-UAVs meets in air, the assigned S-UAV is directed to sepat and then onto the transporter UGV respectively. After the S-UAVs meets in air, the auxiliary S-UAV turn into the new assigned S-UAV. After the assigned S-UAV lands on the transporter UGV, it turns into the new auxiliary S-UAV and waits for the take-off command from the UAD algorithm that checks battery charge level of the current assigned S-UAV. The task take on process of S-UAVs is achieved continually with this method.

APM board is an autopilot was designed to use in unmanned surface, aerial and ground vehicles. In the proposed system, S-UAVs was controlled with APM flight controller that has an external compass and GPS, an internal barometer, a gyroscope with 3 axis, and an accelerometer. Communication between APM controllers and the central computer is achieved with radio telemetry devices. CCD cameras were integrated to S-UAVs and the transporter UGV to obtain the view of the mission area. Analog video receiver and transmitter kits were used to transfer onboard camera image to the central computer. Onboard camera image were transformed to digital signal in order to input them into the central computer. On board camera image were displayed by using software of the analog to digital transformer equipment. Equipment on unmanned vehicles are given in Table 1.

Table 1: Main equipment on unmanned vehicles.

Flight Controller	GPS and Compass	Gyroscope and Accelerometer	Frame	Radio telemetry
APM 2.6	3DR u-blox	MPU - 6000	F 450 quad-copter frame	3 DR 915 MHz



Experimental test configuration of the developed system is illustrated in Figure 9.

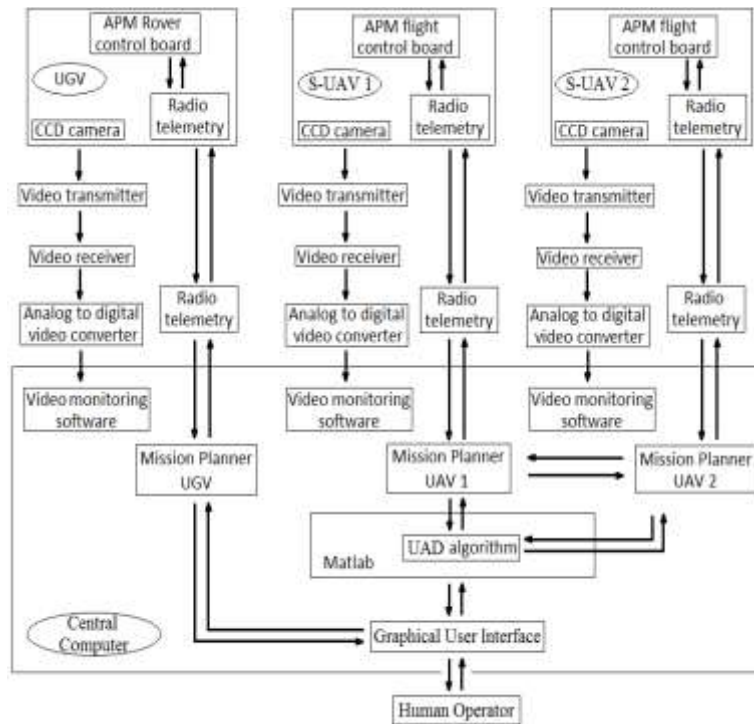


Figure 9: Configuration of the experimental tests of the developed system

Transporter UGV is a differential drive vehicle whose movement is provided with two separate wheels. Desired linear and angular velocity of the transporter UGV might be obtained by changing the rotational speeds of the wheels. Two free wheels were integrated to vehicle chassis to balance the robot. Landing and take-off of S-UAVs were achieved on the separate parts of a platform that was integrated on the transporter UGV. The experimental configuration of our proposed system is given in Figure 10.



Figure 10: Experimental configuration of the proposed system

## RESULTS

A sample application was performed in experimental and simulation tests, and the results of the tests were presented under this section. In sample application, a human operator manually steered the transporter UGV with two quad-copter S-UAVs to a pmp. After the transporter UGV reached to selected pmp, S-UAVs started to perform the surveillance mission.

In simulation of sample application, mr was defined as 200 meters and sepat was defined as 20 meters. By placing mr and sepat in Eq. 3 and in Eq. 4, TEDL and ERL were obtained as 40.92 and 20.46 respectively. In this situation, the auxiliary S-UAV should take off when the assigned S-UAV's battery level exceeds 40.92% and the assigned S-UAV urgently returns to the transporter UGV when its battery charge level exceeds 20.46%. In sample application, it was accepted that pmp of the transporter UGV as the origin. Human operator started to direct the assigned S-UAV that has maximum speed of 3 m/s in x, y and z directions. When the assigned S-UAV's battery level exceeds 40.92%, the auxiliary S-UAV took off. The auxiliary S-UAV equalized its yaw angle to the yaw angle of the

assigned S-UAV while it was moving to sepat. When the auxiliary S-UAV arrived to sepat, the assigned S-UAV was at coordinates of  $X=60$  m,  $Y=100$  m,  $Z=25$  m. When auxiliary S-UAV reached to sepat, it started to track the assigned S-UAV and arrived to the position of its target. The auxiliary S-UAV met the assigned S-UAV within 56.4 seconds. The auxiliary S-UAV passed 189 meters to meet the assigned S-UAV. Battery charge level of the assigned S-UAV was at 9.28% when it landed its platform on the transporter UGV. In experimental tests of sample application, human operator started to direct the assigned S-UAV that has maximum speed of 3 m/s in x, y and z directions. When the assigned S-UAV's battery level exceeds 40.92%, the auxiliary S-UAV took off. The auxiliary S-UAV equalized its yaw angle to the yaw angle of the assigned S-UAV while it was moving to sepat. When the auxiliary S-UAV arrived to sepat, the assigned S-UAV was at coordinates of  $X=60$  m,  $Y=100$  m,  $Z=25$  m. When the auxiliary S-UAV reached to sepat, it started to track the assigned S-UAV and arrived to the position of its target. The auxiliary S-UAV met the assigned S-UAV within 59.7 seconds. The auxiliary S-UAV passed 198 meters to meet the assigned S-UAV. Battery charge level of the old assigned S-UAV was at 7.73%, when it landed its platform on the transporter UGV. Difference between the simulation and experimental tests occurred because of non-ideal conditions of real test environment. Navigation parameters and variables of S-UAVs during tracking process carried out in experimental test of the sample application are given in Table 2.

Table 2: Navigation parameters during tracking.

UAV	Start Position	Time passed during tracking	Distance passed during tracking	Remained battery charge level(at meeting position)
Assigned S-UAV	$x=60$ , $y=100$	59.7 sec	166 meters	24.96%
Auxiliary S-UAV	$x=0$ , $y=0$	59.7 sec	198 meters	81.55%

Figure 11 illustrates the path of the auxiliary S-UAV and the assigned S-UAV while the PN-based tracking was carried out within experimental tests.

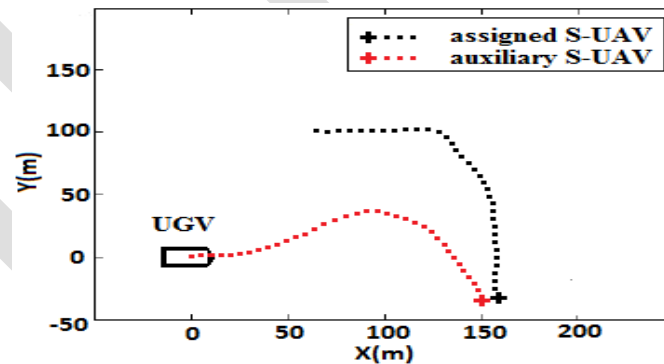


Figure 11: Path of the auxiliary and the assigned S-UAVs

## CONCLUSION AND FUTURE WORK

In this study, a cooperative ISR-based system of unmanned ground and aerial vehicles that is proper to use for remote surveillance of hazardous conditions for humans was proposed. The proposed system was tested with a sample application including a surveillance mission that was carried out in simulation and real experimental environment. The S-UAVs completed the mission without encountering running out of their battery charge during their mission. This demonstrates the validity of the approach that we used to define battery consumption of the S-UAVs.

S-UAVs access position of the transporter UGV via the connection that was established between Mission Planner programs in central computer. Therefore S-UAVs can move to the transporter UGV but cannot land on their platform automatically because their GPS are not precise enough. It is clear that a sub-system that will provide a precise auto landing should be integrated to the S-UAVs of the proposed system. Auto landing sub-system was not integrated in current status of our proposed system. Therefore landing of the S-

UAVs was carried out via remote controllers by the human operator. It is hard and time-consuming method to carry out precise landing of the S-UAVs onto their marked part of the take-off/landing platform by directing them only according to onboard camera view. If the proposed system is carried out in a large target area, our proposed system that includes two S-UAVs might not perform an efficient surveillance on such a large mission area. To overcome this, quantity of unmanned vehicles should be increased. The previous work of the authors that is based on dividing the mission to balanced parts might be used to obtain the minimum number of required unmanned vehicles [24].

In proposed system, ranges of video transfer system and radio telemetry were 300 meters and 1000 meters respectively. Thus, when the surveillance mission was carried out in limits of the video transfer and telemetry devices, problems that were related with video signal and flight data transfer were occurred. This prevents to apply the proposed system in long range tests. In order to overcome this problem and guarantee a success communication, more advanced communication approaches such as GSM communication and long range video transfer devices should be integrated to the proposed system.

In this paper, the consumption of electrical batteries of the S-UAVs was defined with a predictive and approximate approach. Therefore results that were obtained while dynamic tracking process of S-UAVs might change according to variables that were not considered in our work such as agility of the assigned S-UAVs movement, wind direction and speed, and so on. A more certain consumption formulation for batteries of S-UAVs should be developed to obtain more precise results.

Authors will focus to design an auto landing system and to design a battery swapping mechanism for S-UAVs. The planned auto landing sub-system will be designed by using ultrasonic sensors and image processing methods that will use onboard camera view. Implementation of a battery swapping mechanism for S-UAVs is a hard work. However, swapping the battery of S-UAVs is a very proper solution when a surveillance mission requires quick actions.

## REFERENCES:

- [1] Caska S, Gayretli A. "A Survey of UAV/UGV Collaborative Systems". *CIE44 & IMSS'14 Conference*, Istanbul, Turkey, 14-16 October 2014.
- [2] Ercan C, Gencer C. "Literature Review of Dynamic Unmanned Aerial System Routing Problems and Proposals For Future Studies of UASs". *Pamukkale University Journal of Engineering Science*, 19(2), 104-111, 2013.
- [3] Bürkle A, Segor F, Kollmann M. "Towards Autonomous Micro UAV Swarms". *Journal of Intelligent and Robotic Systems*, 61, 339-353, 2011.
- [4] Oh S, Suk J. "Evolutionary controller design for area search using multiple UAVs with minimum altitude maneuver". *Journal of Mechanical Science and Technology*, 27(2), 541-548, 2013.
- [5] Frontoni E, Mancini A, Caponetti F, Zingaretti P, Longhi S. "Prototype UAV helicopter working in cooperative environments". *IEEE/ASME international conference on Advanced intelligent mechatronics*, Zurich, Switzerland, 4-7 September 2007.
- [6] Nigam N, Bieniawski S, Kroo I, Vian J. "Control of Multiple UAVs for Persistent Surveillance: Algorithm and Flight Test Results". *IEEE Transactions on control systems technology*, 20(5), 1236-1251, 2012.
- [7] Wang Z, Mingyang L, Khaleghi A, Xu D, Lobos A, Vo C, Lien J, Liu J, Son Y. "DDDAMS-based Crowd Control via UAVs and UGVs". *2013 International Conference on Computational Science, Procedia Computer Science*, 18, 2028-2035, 2013.
- [8] Tripathi B, Mishra S, Garg S, Kumar A. "An RF Relay Based Control and Communication System for Unmanned Ground Vehicle and Micro Air Vehicle". *2nd International Conference on Computing for Sustainable Global Development*, New Delhi, India, 11-13 March 2015.
- [9] Saska M, Krajník T, Pireucil L. "Cooperative  $\mu$ UAV-UGV autonomous indoor surveillance". *9<sup>th</sup> International Multi-Conference on Systems, Signals and Devices*, Chemnitz, Germany, 20-23 March 2012.
- [10] Perkins T, Murphy R. "Active and Mediated Opportunistic Cooperation Between an Unmanned Aerial Vehicle and an Unmanned Ground Vehicle". *IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*, Linköping, Sweden, 21-26 October 2013.
- [11] Hui C, Yousheng C, Xiaokun L, Shing W. "Autonomous takeoff, tracking and landing of a UAV on a moving UGV using onboard monocular vision". *32nd Chinese Control Conference*, Xi'an, China, 26-28 July 2013.
- [12] Langerwisch M, Wittmann T, Thamke S, Remmersmann T, Tiderko A, Wagner B. "Heterogeneous Teams of Unmanned Ground and Aerial Robots for Reconnaissance and Surveillance - A Field Experiment". *11th IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*, Linköping, Sweden, 21-26 October 2013.
- [13] Kruijff G, Tretyakov V, Linder T, Pirri F. "Rescue Robots at Earthquake-Hit Mirandola, Italy: a Field Report". *11th IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*, Texas, USA, 5-8 November 2012.
- [14] Capitan J, Merino L, Ollero A. "Cooperative Decision-Making Under Uncertainties for Multi-Target Surveillance with Multiples UAVs", *Journal of Intelligent and Robotic Systems*, 61, 1-16, 2011.
- [15] Chen J, Zhang X, Xin B, Fang H. "Coordination Between Unmanned Aerial and Ground Vehicles: A Taxonomy and Optimization Perspective". *IEEE Transactions on Cybernetics*, 99, 1, 2015.

- [16] Fujii K, Higuchi K, Rekimoto J. "Endless Flyer: A Continuous Flying Drone with Automatic Battery Replacement". *IEEE 10th International Conference on Ubiquitous Intelligence & Computing and 2013 IEEE 10th International Conference on Autonomic & Trusted Computing*, Salerno, Italy, 18-21 December 2013.
- [17] Suzuki K, Filho P, Morrison J. "Automatic Battery Replacement System for UAVs: Analysis and Design". *Journal of Intelligent and Robotic Systems*, 65, 563-586, 2012.
- [18] Tan R, Kumar M. "Tracking of Ground Mobile Targets by Quadrotor Unmanned Aerial Vehicles". *Unmanned Systems*, 2(2), 157–173, 2014.
- [19] Chi Q, Bole B, Hogge E, Vazquez S, Daigle M, Celaya J, Weber A, Goebel K. "Battery Charge Depletion Prediction on an Electric Aircraft". *Annual Conference of the Prognostics and Health Management Society*, New Orleans, USA, 14-17 October 2013.
- [20] Voos H. "Nonlinear Control of a Quadrotor Micro-UAV Using Feedback-Linearization". *IEEE International Conference on Mechatronics*, Malaga, Spain, 14-17 April 2009.
- [21] Tayebi A, McGilvray S. "Attitude stabilization of a four-rotor aerial robot". *43rd IEEE Conference on Decision and Control*, Paradise Island, Bahamas, 14-17 December 2004.
- [22] Mazumder S., Dutta S. "Analytical study and Designing of a I-PD controller (a practical Modified PID controller) for a third order system using MATLAB simulation". *International Journal of Engineering Research and General Science*, 3(1), 976-980, 2015
- [23] Evgrafov V, Pavlovsky V, Pavlovsky V E. "Dynamics, Control, and Simulation of Robots with Differential Drive". *Journal of Computer and Systems Sciences International*, 46(5), 836–841, 2007.
- [24] Caska S, Gayretli A. "An Algorithm for Collaborative Patrolling Systems with Unmanned Air Vehicles and Unmanned Ground Vehicles". *7th International Conference on Recent Advances in Space Technologies (RAST)*, Istanbul, Turkey, 16-19 June 2015